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Short-circuit Analysis of Solenoid and Pancake Type Bifilar Winding Magnets using BSCCO tape

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***Abstract*— To verify the feasibility of bifilar winding type superconducting fault current limiter (SFCL) using BSCCO tape, two types of magnets were fabricated and tested by short-circuit in this research. Even if the FCL using high Tc superconducting (HTS) tape has zero resistance in normal state, it needs to be wound as a bifilar winding for zero inductance. Solenoid type and pancake type bifilar winding magnets are designed and fabricated with the same length of BSCCO tape. The test system consists of AC power supply, transformer, fault switch, load and bifilar winding magnet. The applied AC voltages during fault duration, 0.1s, were from 0.5V to 20V. The test results without bifilar winding magnet were compared with those with each type magnets. The test results include voltage against magnet, transport current and generated resistance curve. Thermal stability, the recovery time, was studied from the results of two type magnets. The pancake type was the most effective to limit fault current but the solenoid type was thermally the most stable. From this research, short-circuit characteristics of the two types were obtained.**

1. INTRODUCTION

Various types of SFCL are developed in many countries as a solution to reduce the increasing fault current levels in present power grid. SFCL generates large impedance immediately when the fault current flows through it [1][2]. BSCCO tapes are used for a SFCL in this research. Because the HTS tapes are used as bifilar winding method, the SFCL is called bifilar winding type FCL. In this paper, bifilar winding magnets using BSCCO tapes are designed, fabricated and tested by short circuit to show the feasibility of bifilar winding type SFCL. The magnets have bifilar winding to remove the inductance which induces voltage drop and loss in power grid, at the normal state [3]. Two types of bifilar winding, solenoid and pancake types are compared with each other type in thermal, mechanical and limiting characteristic points of view. Through this research, the feasibility of bifilar winding type SFCL using BSCCO tape was studied. Characteristics, advantages and disadvantages, of each types of bifilar winding magnet were also studied.

2. BIFILAR WINDING MAGNETS

2.1. Design of Bifilar Winding Magnets

In order to get large enough impedance of the SFCL by using HTS tape when the fault current flows, a long HTS tape is required. Winding is required to apply long wire to make a SFCL. SFCL should have unique characteristics having no impedance when the normal state current flows. So the HTS tape must be wound as bifilar winding to make SFCL non-inductive. Magnetic field is generated around wire when a current flows through wire. Therefore it should be possible to make almost non- inductive if two adjacent wires have opposite direction current flow. There were many different bifilar winding designs. Because they are easy to be fabricated and the pancake type has better non-inductive characteristic than any other bifilar winding has, we designed the solenoid and the pancake type bifilar windings.

2.2. Fabrication of Bifilar Winding Magnets

Each magnet is wound with stainless steel reinforced BSCCO tape of American Superconductor Corporation (AMSC). This HTS tape has about 115A of critical current at 77K, under self field. The width and thickness are 4.1mm and 0.3mm, respectively. Both Solenoid and pancake type bobbins are made of G-10 fiber reinforced plastic. In order to test each magnet in the same condition except types of magnet, the same length of BSCCO tapes is used to have the same resistance at room temperature.

2.2.1. Solenoid Type Magnet

The HTS tape requires more careful treatment than a normal conductor. The magnet was wound with constant winding tension along the very precise turn pitch. Total length of HTS tape in a magnet is 720cm. In the upper and lower sides of the bobbin, there are three copper blocks for fixing and connecting two tapes to make bifilar winding. A connecting copper block is a weakness of the bifilar winding magnet. Because the copper is normal conductor, it causes slower switching characteristic of the magnet which is a disadvantage of FCL application.

Fig. 1 is a fabricated solenoid type bifilar winding magnet. Two tapes are wound simultaneously and they are connected at the copper block at lower side of the bobbin. The current flows in an opposite direction in turns to make bifilar winding. The inductance of this module is 2.08μH and the resistance at room temperature is 261mΩ .

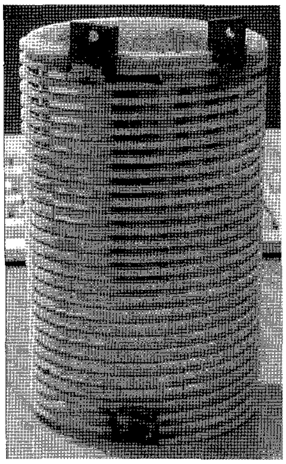


Fig. 1. Fabricated solenoid type bifilar winding magnet.

2.2.2. Pancake Type Magnet

In pancake type case the winding machine for the HTS pancake was used. This machine can wind the coil with constant winding tension by powder breaker.

To make the bifilar winding, the bobbin has unique shape in pancake type magnet. According to general pancake winding method, the tape is wound with one direction and currents also flow to the direction which induce high magnetic field. Two adjacent tapes should have opposite direction of current path to be non-inductive. The curved path on pancake type bobbin is suggested to make bifilar winding. It is the most efficient winding of the other bifilar windings because it can totally cancel off magnetic field. Total length of HTS tape in a module is same as solenoid type of 720cm. And the inductance of this magnet is 0.53μH which is much smaller than that of solenoid type, 2.08μH. The resistance at room temperature is 251mΩ. The pancake has no connection part, so it has relatively good switching characteristic of the magnet.

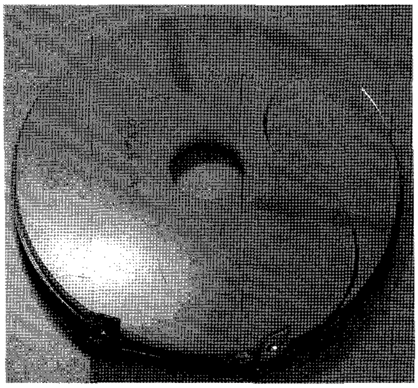


Fig. 2. Fabricated pancake type bifilar winding magnet.

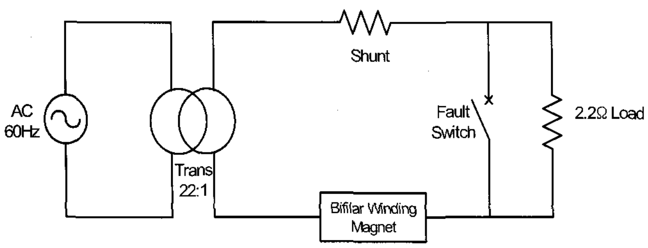


Fig. 3. Schematic of current limiting test.

3. SHORT-CIRCUIT TEST

3.1. Condition of the Short-Circuit Test

The SFCL has ability to reduce the fault current by resistance when the superconductor is quenched due to over current above critical current. The short circuit tests are required to know the quench characteristics of HTS bifilar magnets. The short circuit test in this research is similar to a real fault current accident in power grid. But the test was performed by single phase accident. Fig. 3 is the schematic of short circuit test. All signals are acquired and processed in DAQ processor and board.

Because of the limitation of electric power source, the maximum available current by power source was set to $75A_{rms}$. In order to enlarge the current flowing through the magnet, a 22:1 ration transformer was introduced. The current which flows in secondary winding is allowed to $1650A_{rms}$. The AC power supply generates voltage in primary winding and actual source to the magnet is the secondary winding of transformer. In normal state the current in secondary winding flows through the load which has the impedance of 2.2 ohm. To simulate the fault occurrence, the fault switch which can control the fault duration from 0.01s to 100s was developed in parallel to the load. In this research the fault duration was 0.1s, 6 cycles. The liquid nitrogen was used as a cryogen so that the operating temperature was 77K.

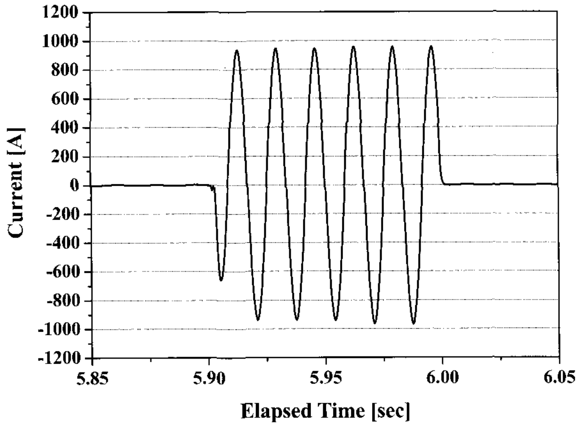


Fig. 4. Current flow without current limiting magnets at $5V_{rms}$.

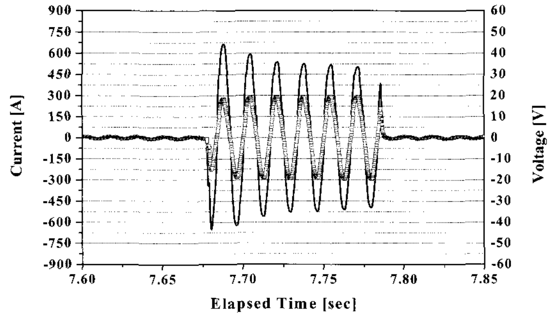
3.2. Experimental Results

In order to know the line impedance or other impedance such as secondary winding impedance and resistance of fault switch, the short circuit test was performed without magnet. Fig. 4 is the test result at $5V_{rms}$ test and the primary voltage of power supply was $110V_{rms}$. Unless there is the FCL module, the current flows up to $950A_{peak}$ in secondary winding. About 7.4mΩ of impedance is calculated from the result. Through this calculated impedance peak current without bifilar magnet can be predictable.

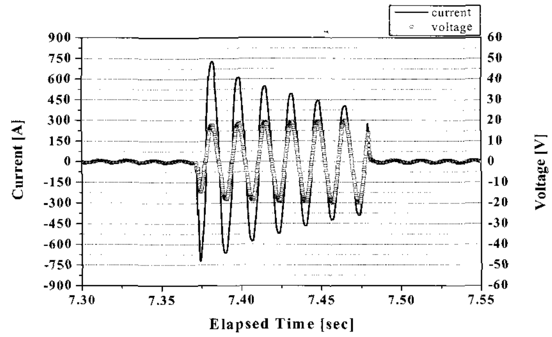
Fig. 5 shows the test results at $0.4V_{rms}$ test. Difference of phase between current and voltage is noticeable in the result under the critical current. It is because the inductance is main impedance while resistance of the bifilar magnet is zero. The pancake type bifilar winding magnet has small inductance. Solenoid type has 4 times higher inductance than pancake type. Though the resistance is zero under critical current, residual inductance acts as the impedance of the circuit. The impedance in normal state is a defect in FCL application and solenoid type has higher voltage drop at $0.4V_{rms}$ test than pancake type magnet. The current at $0.4V_{rms}$ test was maximum $81A_{peak}$ in the Fig. 5(b) which is under critical current.

Fig. 6(a) is the results of solenoid type bifilar winding magnet test and Fig. 6(b) is the results of pancake type test at $16V_{rms}$ test. Fault current can be estimated about $2160A_{rms}$ from calculated line resistance. Fault current was reduced to 664A in first peak and 503A in last peak at the test of solenoid type. In case of pancake type, fault current was reduced to 726A in first peak and 405A in last peak.

At the same condition, the solenoid type limits the fault current to lower level than pancake type in first peak. The different limiting characteristic in first peak strongly depends on the resistance of silver matrix and stainless steel at 77K because the temperature rise is not so large in the first peak. After 0.1 second, the end of the fault duration, the pancake type bifilar winding magnet has higher resistance so as to reduce the fault current to $405A_{peak}$ than the solenoid type magnet has.

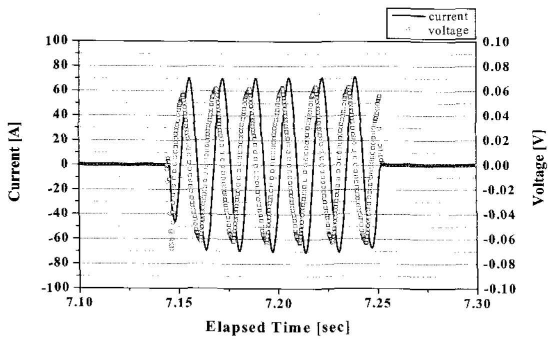


(a)

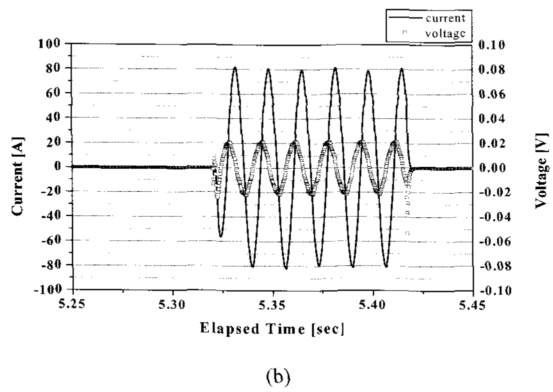


(b)

Fig. 6. $16V_{rms}$ test results of (a) solenoid type (b) pancake type line is current and dot is voltage.



(a)



(b)

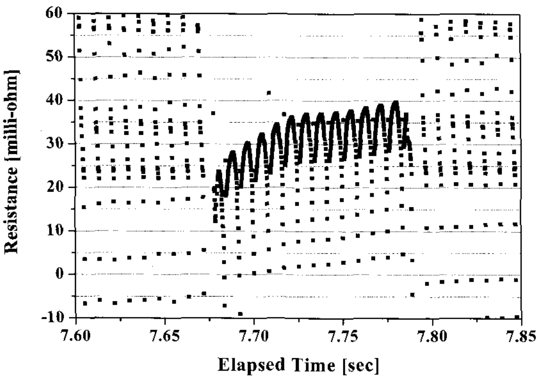
Fig. 5. $0.4V_{rms}$ test results of (a) solenoid type (b) pancake type, line is current and dot is voltage.

The pancake magnet was wound as if the tapes were stacked, so the heat generated could accumulate in the magnet. The pancake type has higher resistance in the same condition.

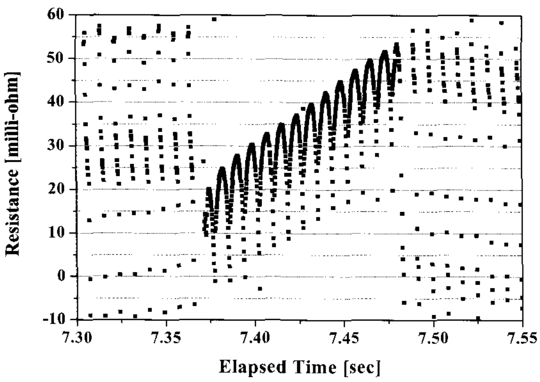
Fig. 7 shows generated resistance in $16V_{rms}$ test. Solenoid type magnet makes $23m\Omega$ in the first peak and final resistance is about $40m\Omega$. There exists residual inductance even if it is the bifilar module. The inductance causes voltage drop with 90 degree phase different from current in normal state. So the impedance in normal state was seemed like a noise which is shown in Fig. 7. In case of solenoid type, the curve increases steeply to 0.05 second after the fault occurs and the slope became lower. It means that cooling energy is similar to generating energy after 50ms. So this type is thermally stable and it can endure high current which causes high energy.

Pancake type bifilar winding magnet has a quite different pattern from solenoid type. It makes $20m\Omega$ in the first peak which is almost same with solenoid type. In final peak the pancake makes resistance about $55m\Omega$.

And resistance continuously increased to the last peak. It is because the heat generated during the fault by joule heating. So this type has good characteristic for view point of resistance generation.



(a)



(b)

Fig. 7. $16V_{rms}$ test results of generated resistance of (a) solenoid type (b) pancake type.

3.3. Discussion

We know that solenoid and pancake type bifilar winding magnets have a quite different quench characteristic from the short-circuit test. Both types can be properly used in different user's condition. Solenoid type can be applied to the large scale power system because it has good thermal stability when the high fault current flows and good insulating characteristic against high voltage. Pancake type is able to be used in small scale system like protecting electrical equipments and electronic devices. It is easy to make high resistance at the low voltage in pancake type bifilar winding magnet compared with solenoid type magnet.

4. CONCLUSION

Solenoid and pancake type bifilar winding magnets by using BSCCO tape were designed and fabricated. To make simulation of similar fault situation in real power grid, short-circuit test was performed. Pancake type module could generate higher resistance than solenoid type. Because the pancake type is able to accumulate the heat more than solenoid type in structure point of view, it could reduce the fault current more. The pancake type is closer to non-inductance which is relative with operation efficiency at normal state. Because the solenoid type magnet has lager surface to liquid nitrogen than the pancake type, it has good characteristic of thermal stability which is other important factor of FCL application. This thermal stability causes the solenoid type to have a good recovery time [4].

The bifilar winding type SFCL using BSCCO tape has many advantages comparing other type SFCL. This research is one of the feasibility verifying experiments. Therefore more progressive researches about bifilar winding type SFCL should be conducted.

ACKNOWLEDGMENT

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